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Summary

Collaborative Decision Making (CDM) is about improving the way different actors in the handling of air traffic (ATM service providers, airlines, airport authorities, pilots, etc.) co-operate at an operational level. In this paper, we consider slot swapping, one of the CDM applications for slot allocation. Slot swapping allows airlines to prioritise flights by exchanging the slot of a flight with the slot of another flight. This can for example take place when there is a commercially sensitive flight (e.g. with many transfer passengers) with a long delay and there is a possibility to advance this flight by simultaneously delaying another flight.

The development of slot swapping in Europe is still in its initial phase. In a EUROCONTROL study a preliminary description of a slot swapping application based on Most Penalising Regulation is given. In this paper we address a more general way of slot swapping. We present three different applications for slot swapping: swap at departure time, swap at sector arrival, and swap at load contribution. For each application, we give algorithms for finding the possible swaps. The three algorithms have been implemented in a prototype. The computational results obtained from this prototype look promising, because they indicate that there are feasible swap opportunities for a significant part of the delayed flights.

One of the benefits of slot swapping is, for example, that by prioritising flights with many passengers, the number of passengers with a delay may decrease. Moreover, by prioritising a flight with many transfer passengers, the delay of a connecting flight can be prevented. Although the operational consequences have to be investigated further, the developed slot swapping applications look promising and seem to be useful for ATM in the near future.

Contents

(18 pages in total)

1 Introduction

Collaborative Decision Making (CDM) is about improving the way different actors in the handling of air traffic (ATM service providers, airlines, airport authorities, pilots, etc.) co-operate at an operational level. It is a process in which different actors improve the exchange of information, take into account information from others and even may distribute decision making. CDM has been identified as one of the key elements of the ATM 2000+ strategy [4]. In a study by EUROCONTROL [5] different possible applications of CDM have been identified. Moreover, CDM is one of the five core technologies in the FAA’s Free Flight program (see [10]).

In this paper, we consider CDM applications for slot allocation. Slot allocation assigns a time slot for departure to a given collection of flights in order to avoid overload at airports and in controlled sectors. An important CDM appliation for slot allocation is slot swapping. Slot swapping allows airlines to prioritise flights by exchanging the slot of a flight with the slot of another flight. This can for example take place when there is a commercially sensitive flight (e.g. with many transfer passengers) with a long delay and there is a possibility to advance this flight by simultaneously delaying another flight.

In current practice, slot allocation is centrally performed by the CFMU in Brussels. The CFMU uses the CASA algorithm. During the last years, a significant amount of research on alternative methods for slot allocation has been performed (see e.g.[1], [3], [6], and [9]). This research reveals that with mathematical optimisation methods it is possible to decrease the delays significantly. However, while CASA optimises the currently used equity concept, the extent in which others methods ensure a desirable equity has to be investigated. As a basis for the experiments in our study on slot swapping, we have used the Optislot algorithm (see [6]). Still, the slot swapping methods that have been developed are applicable to any type of slot allocation scheme.

Slot swapping is part of the Ground Delay Program Enhancements in the US (see [2] and see [11] for overview of this program). The situation in Europe is different because in Europe the capacity of en-route controlled sectors is a limiting factor and therefore has to be taken into account explicitly, while this is hardly the case in the US.

The development of slot swapping in Europe is still in its initial phase. Report [5] contains a preliminary description of the slot swapping application. In this paper we address a more general way of slot swapping. We present three different applications for slot swapping. Together with these applications, we also give algorithms for finding the possible swaps. The three algorithms have been implemented in a prototype. We present computational results obtained from this prototype for each of the three methods and we assess the benefits of slot swapping by these methods. A more elaborate description of the contents of the paper is given in [7].

The paper is organised as follows. In Section 2, we present the three slot swapping applications and algorithms. In Section 3, we report on computational experiments. Finally, in Section 4 we conclude the paper and assess the benefits of the slot swapping applications.

2 Applications and algorithms

2.1 Introduction

First, we introduce some notation that we need to describe the algorithms.

F	The set of flights.
S	The set of regulated sectors in airspace.
I	The set of time intervals.
$C(\mathrm{s},i)$	The capacity of sector $s\in S$ in a given time period $i\in I$ is the maximum number of flights that are allowed to arrive at sector s in time interval i.
$L(s,i)$	The allocated load or used capacity of sector $s\in S$ in time period $i\in I$.
$d_0^f \in T$	The scheduled departure time for flight $f\in F$.
$d^f \in T$	The allocated departure time or departure slot for flight $f\in F$.
$d_{s,in}^f$	The time that flight $f\in F$ needs to fly from departure to sector $s\in S$.

The time intervals I form a division of the total time period during which the slot allocation schedule is used. Typically this latter period is an interval within a 24 hours period. The main purpose of the time intervals lies in the definition of the capacity constraints that are defined over intervals.

The scheduled departure time d_0^f is also referred to as the earliest departure time. It is the time that a flight is ready for departure regardless of the slot allocation schedule. In the context of this paper we use the terms departure time and departure slot as if they are interchangeable. In reality the departure slot typically denotes a 15 minutes period that starts 5 minutes before and ends 10 minutes after the allocated departure time. Since the departure time uniquely defines the departure slot, and vice versa, we can use both terms without ambiguity.

Slot swapping as proposed by EUROCONTROL is based on a slot allocation scheme provided by CFMU using the CASA algorithm. The CASA algorithm is based on a First Come First Served (FCFS) principle and it defines a Most Penalising Regulation (MPR) for a flight. The MPR is the regulation that gives the flight the greatest delay, if it would be the only regulation. In the slot swapping applications that EUROCONTROL proposes flights can only be swapped if they have the same MPR. In this paper we consider three applications that are more general than a swap algorithm based on MPR.

In the next subsections, we describe the applications in detail. For each application, we describe the exact situation in which a swap can take place. Based on this exact situation description the corresponding algorithm identifies possible swaps. This algorithm can be used in three situations: to determine a swap for a give pair of flights (if there is one), to determine for a given delayed flight all possible swaps with other flights, and to determine all possible swaps within a given collection of flights.

2.2 Swap at departure time

A flight slot is usually associated with the allocated departure time of a flight, so a natural first candidate for slot swapping is an exchange based on departure times of flights. Let $f_1, f_2 \in F$ denote two flights, that depart from the same airport. We assume that the flights have roughly the same cruising speed, they go through the same single regulated sector, but they have different destinations. An example is depicted in Figure 1.

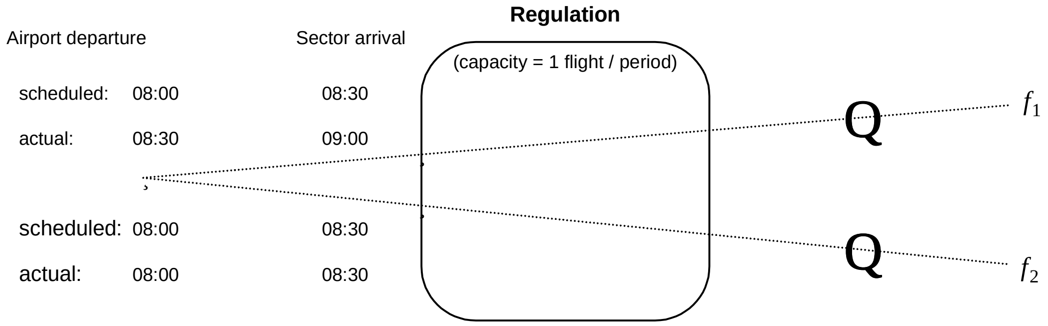

Figure 1. Example of slot swapping at departure time

The regulation has a capacity of one flight per hour, where each period starts and ends exactly on the hour. Flight f_2 is allowed to depart at its scheduled time 08:00. Since flight f_2 is using the sector capacity between 08:00 and 09:00, flight f_1 is not allowed to arrive at the sector before 09:00, so it has to be delayed 30 minutes. If for some reason flight f_1 should be given priority over flight f_2, then a possible solution might be to swap the departure times of both flights, so flight f_1 would depart at 08:00 and flight f_2 would depart at 08:30. Such a swap of departure times would not violate the restriction that a flight is not allowed to depart before its scheduled departure time.

To determine if a swap is feasible two kinds of conditions have to be checked: firstly, the flights are not allowed to depart before their scheduled departure and secondly the swap is not allowed to cause capacity overload.

The conditions that guarantee that the flights do not depart before their scheduled departure time are as follow. If before swapping flight f_1 departs later than flight f_2, then:

$$d_0^{f_1} \le d^{f_2} < d^{f_1}, \tag{1}$$

After swapping the two flights the new departure time for flight f_1 would become d^{f_2}, the current departure time of flight f_2. For this swap to be feasible the new departure must not be earlier than the scheduled departure time $d_o^{f_1}$ of flight f_1 (the first inequality of (1)). The second inequality of (1) simply states that f_1 departs later than f_2. A similar expression (2) deals with the situation where before swapping flight f_2 departs later than flight f_1:

$$d_0^{f_2} \le d^{f_1} < d^{f_2}, \tag{2}$$

It is possible to add extra constraints, for instance to enforce an upper bound on the departure time for a flight that is swapped to a later departure.

Besides the conditions (1) or (2) we also need to check if the sectors do not get overloaded by the swap. This is a fairly easy operation, since for this we just need to update the load matrix for the two flights only. Note that it is not necessary that both flights depart from the same airport.

2.3 Swap at sector arrival time

In the slot allocation process, the regulated sectors form the bottleneck. Therefore, one may say that the issue in slot allocation is the planning of the arrival times of flights in regulated sectors. For example, the CASA algorithm applies the first-come-first-served principle on the basis of scheduled arrival times at regulated sectors. This observation leads to the idea of swapping based on flight arrival times at sectors.

Again we let $f_1, f_2 \in F$ denote two flights that share a sector $s \in S$, which is regulated. The two flights do not necessarily depart from the same airport. The scheduled and the actual arrival times of a flight $f \in F$ at sector s are $d_0^f + d_{s,in}^f$ and $d^f + d_{s,in}^f$, respectively. Swapping at sector arrival time is defined as changing the departure times of flights f_1 and f_2 so that the actual arrival times of the two aircraft at sector s are interchanged. An example is pictured in Figure 2.

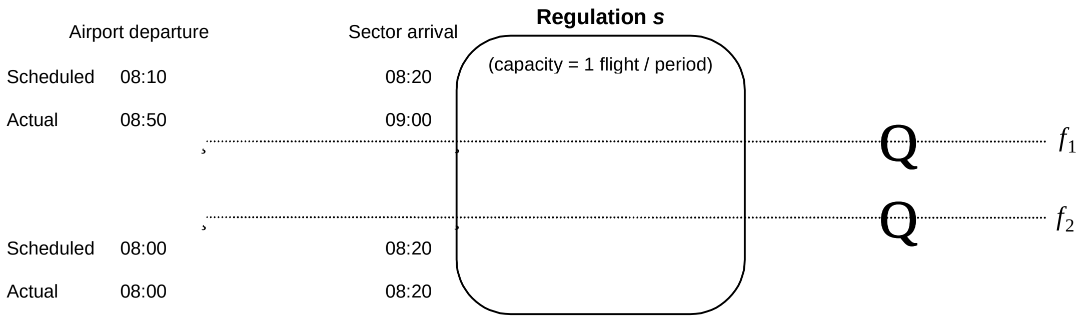

Figure 2. Example of slot swapping at sector arrival time

In this example flight f_1 is delayed by 40 minutes, while flight f_2 leaves on time. It is not permitted to swap the two flights at departure time, since flight f_1 is not allowed to depart at 08:00. The flight can be swapped at sector arrival time. Such a swap implies that flight f_1 will arrive at sector *s* at 08:20 (i.e. the actual and scheduled arrival time at sector *s* for flight f_2). For flight f_1 to arrive at sector *s* at 08:20, it will have to depart from the airport at 08:10, which is feasible. After the swap flight f_2 will arrive at sector *s* at 09:00, for which it has to depart from its airport at 08:40. This is a feasible departure time for this flight.

Again, to determine if a swap is feasible the following conditions have to be checked: firstly, the flights are not allowed to depart before their scheduled departure and secondly the swap is not allowed to cause capacity overload.

The conditions that need to be satisfied to guarantee that the flights do not depart before their scheduled departure can be formalized as follows.

$$d_0^{f_1} + d_{s,in}^{f_1} \leq d^{f_2} + d_{s,in}^{f_2} < d^{f_1} + d_{s,in}^{f_1} \qquad (3)$$

The inequalities in (3) correspond to the case where before the swap flight f_2 arrives at sector *s* earlier than flight f_1, which is stated exactly in the second inequality of (3). The first inequality states that the scheduled arrival time for flight f_1 at sector *s* is earlier than the sector arrival time of flight f_1 *after* the swap, which is of course the scheduled sector arrival time of flight f_2. In a similar way, in the case when before the swap flight f_1 arrives at sector *s* earlier than flight f_2 these conditions can be formulated as follows:

$$d_0^{f_2} + d_{s,in}^{f_2} \leq d^{f_1} + d_{s,in}^{f_1} < d^{f_2} + d_{s,in}^{f_2} \qquad (4)$$

It is possible to add a similar upper bound constraint on the new departure times as was sketched for slot swapping at departure time.

Again in this method, we have to check whether the sector capacities are not violated after the swap. This is done in the same way as in the previous section, namely by updating the load matrix for the two flights.

2.4 Swap at load contribution

The allocated load, and hence the possible capacity overload, of the sectors is determined by the time period *i* during which the flights arrive in sectors instead of by the exact arrival time. For this reason, we can be more flexible in swapping on sector arrivals. Unlike the first two algorithms, this algorithm does not swap slots through exchanging times, but by changing a flight's presence in a sector during a certain time period. Each aircraft that passes a sector contributes to the load of that sector at a certain time period. Since the presence of an aircraft in a sector during a certain time period contributes to the load of that sector, we say that this next algorithm is based on swap at load contribution. An example is presented in Figure 3.

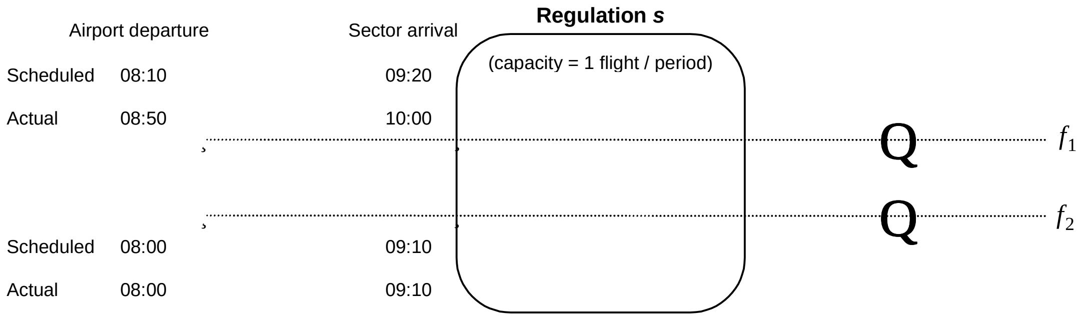

Figure 3. Example of slot swapping at load contribution

We have two flights $f_1, f_2 \in F$ that share a regulated sector $s \in S$. The two flights do not necessarily depart from the same airport. The scheduled and the actual arrival times of a flight $f \in F$ at sector *s* are $d_0^f + d_{s,in}^f$ and $d^f + d_{s,in}^f$, respectively. Flight f_2 arrives at the sector at 09:10 and by this it occupies the whole capacity for this sector between 09:00 and 10:00[1]. This implies that flight f_1 cannot arrive at sector *s* earlier than 10:00, which it can achieve by departing from the airport at 08:50. It is not possible to swap the two flights at departure time (this would require flight f_1 to depart at 08:00 which is before its scheduled departure time) nor to swap at sector arrival time (this would require flight f_1 to arrive at the sector at 09:10, which is before its scheduled arrival time there). It is possible, however, to swap the two flights by

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[1] A capacity of one flight per hour and a travel time through a sector of one hour are not realistic. These values are merely chosen for clarity of the presentation of the swap by load contribution algorithm. Realistic values in Europe are a travel time through a sector of around 10 minutes, the length of a period equal to 20 minutes, and a capacity between 15 and 20 aircraft per period. The principles of the swap by load contribution algorithm remain the same for these values.

swapping their contribution to the load of the sector. For this we need the load contribution table which is represented in Table 1.

		Regulation *s*				
period *i*	…	08:00-09:00	09:00-10:00	10:00-11:00	11:00-12:00	…
flight f_1	…		0	1	0	…
flight f_2	…		1	0	0	…
load $L(s,i)$	…		1	1	0	…
capacity $C(s,i)$	…	1	1	1	1	…

Table 1. Load contribution table for the example of Figure 3.

In this load contribution table each regulation is represented by a number of columns, one for each time period that the sector is regulated. Each flight is represented by a row. A one in the row of a flight corresponds to the time period that this flight crosses the regulation that corresponds to the column. A zero indicates the time periods that a flight might cross a regulation according to its scheduled departure time. The load or used capacity of a regulation in a time period is the sum of the load contributions of the flights in the corresponding column.

In the example swapping at load contribution would mean that we change the departure times of the flights f_1, f_2 such that f_1 crosses the regulation in time period 09:00-10:00 and flight f_2 crosses the regulation in period 10:00-11:00. This can for instance be accomplished by letting f_1 depart at 08:10 (so it would enter the regulation at 09:20) and let f_2 depart at 08:50 (so it enters the regulation at 10:00).

For a given pair of flights, the load contribution table can be used to find all possible swap opportunities that do not cause overload. Besides this, the swap has to be such that no flight departs before its scheduled departure time. The corresponding conditions can be represented as follows. Assume that flight f_1 needs to be swapped to an earlier time, i.e. before swapping f_1 arrives at the sector after f_2. These conditions can be formulated as:

$$d^{f_2} + d^{f_2}_{s,in} < \left(d^{f_1} + d^{f_1}_{s,in}\right) - \left(d^{f_1} + d^{f_1}_{s,in}\right) \bmod \tau_s , \tag{5}$$

And

$$d^{f_2} + d^{f_2}_{s,in} \geq \left(d^{f_1}_0 + d^{f_1}_{s,in}\right) - \left(d^{f_1}_0 + d^{f_1}_{s,in}\right) \bmod \tau_s , \tag{6}$$

where τ_s is the period length for sector *s* represented in minutes. Condition (5) states that the time period that flight f_2 crosses sector *s* must lie strictly before the time period that flight f_1 passes through the sector. Condition (6) states that the time period of flight f_2 must not be earlier than the earliest time period that f_1 can cross.

A similar set of conditions can be derived for the situation that f_2 needs to be swapped to an earlier time.

In this case, it is also possible to add an upper bound constraint on the new departure times as was sketched for slot swapping at departure time.
Note that with swapping at load contribution there is still a freedom in choosing the departure times after the load contributions have been swapped.

Finally, we can show that the following holds:

Proposition. *If the slot allocation is flight-by-flight optimal, then the application swap at load contribution finds all possible swaps, where a slot allocation is flight-by-flight optimal if no flight can be advanced individually (without delaying other flights).*

3 Numerical Results

The three slot swapping algorithms as presented have been tested on a number of test cases. The three cases represent a days' air traffic above France in 1994 and are described in [8]. The cases consists of a few thousand flights over about 60 sectors for which there are a total of about 1150 regulations. In the test we have used only the first 1000 flights for two cases and the first 1100 flights for the third case. The sector capacities are defined per time period with a length of 30 minutes. For each of these test cases a slot allocation scheme has been computed with the Optislot program (see [6] and [12]). The properties of the test cases are summarized in Table 2.

	Test case No. and date		
	1: Sun 1994-05-08	2: Wed 1994-06-01	3: Thu 1994-06-02
# flights	1000	1000	1100
# sectors	58	59	63
# regulations	1134	1170	1153
# delayed flights	198	145	200

Table 2. Properties of the test cases.

The first results that we discuss concern the number of delayed flights that can be swapped. These numbers are summarised by absolute values (#) and by percentage of the total number of delayed flights (%) in Table 3. For the determination of swap combinations no distinction was made between airlines, since this information was unavailable in the test data. The column "combined" indicates the results when the outcome of swap at departure time and at sector arrival time are combined and the duplicates are removed. The figures indicate that there is a large overlap between the two algorithms. The best results are obtained with the swap at load contribution algorithm. This comes as no surprise, since for every delayed flight the number of possible candidates is largest for the load contribution algorithm. Also the conditions that flights have to satisfy to allow a swap by load contribution are the least strict of the three methods.

	Swap method							
	Departure time		Sector arrival		Combined		Load contrib.	
test case	#	%	#	%	#	%	#	%
1	82	41	81	41	87	44	183	92
2	38	26	40	28	43	30	124	86
3	69	35	69	35	82	41	173	87

Table 3. Number and percentage of swappable flights

The next results concern the number of swap combinations, i.e. the number of pairs of flights (f_1,f_2) that can be swapped. Note that in this number all the swap combinations with one delayed flight are counted separately. The results are presented in Table 4. In this table for each method the total number of swap combinations is given (total) as well as the average number of possible swaps per swappable flight (avg.). The number of possible swap combinations is remarkably large for test case 1. The number of swappable flights (Table 3) does not exhibit this behaviour so much, so there is a definitely larger number of swap candidates for each swappable flight. Investigation of the test data suggests that this may be due to the different capacity demand structure for this case. In test case 1 the overall capacity demand is significantly higher, because the flights on average cross more sectors than the flights in the other two test cases. This explains the large number of swap combinations for swapping at load contribution. Apparently this also leads to almost disjoint swap sets for the swap at departure time and the swap at sector arrival algorithms in test case 1 (compare the column “combined” with swapping at departure time and at sector arrival).

	Swap method							
Test case	Departure time		Sector arrival		Combined		Load contrib.	
	total	avg.	total	avg.	total	avg.	total	avg.
1	550	6.7	287	3.5	732	8.4	5200	28.4
2	82	2.2	64	1.6	92	2.1	1269	10.2
3	135	2.0	129	1.9	168	2.0	1888	10.9

Table 4. Number of swap combinations and average per swappable flight for the test cases.

The computational efforts for the algorithms are minor. The worst case (test case 1 and swapping at load contribution) takes 8 seconds on a low-end SGI Indy 133Mhz MIPS R4600 workstation. On average the algorithms take 1.2 seconds for swap at departure time, 1.7 seconds for swap at sector arrival time and 5.4 seconds for swap at load contribution. The computation time is proportional to the number of candidates that need to be checked for swapping.

The remainder of this section presents some characteristics of swapped flights. In Figure 4 we depict the number of minutes that flights are shifted due to a swap. The numbers are counted over all possible swap combinations. The example of Figure 4 is based on test case 1 and the swap algorithms based on departure time, on sector arrival time and the combination of both. For these algorithms the shifts in time of the two swapped flights are opposite and equal in length. It appears that the shifts are usually moderate, most flights are shifted 30 or 60 minutes.

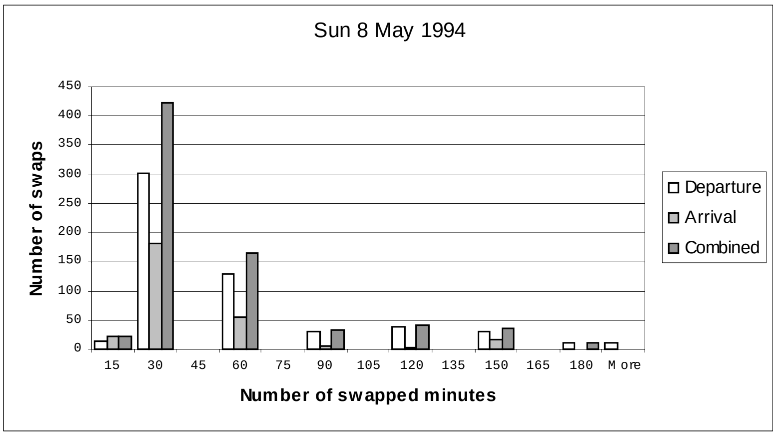

Figure 4. Swapped minutes per flight for test case 1.

In Figure 5 the same data is represented for test case 2. The data for test case 3 is not depicted, but it is similar to test case 2. Shifts in this case are smaller than for test case 1. This is again assumed to be a result of the different demand structure for test case 1. A remarkable feature can be observed in Figure 4. Apart from some swaps that shift flights over a length of 15 minutes, all the other swaps involve shifts over multiples of 30 minutes. This is the length of the time period as defined in the capacity constraints. This phenomenon is not observed in test cases 2 and 3.

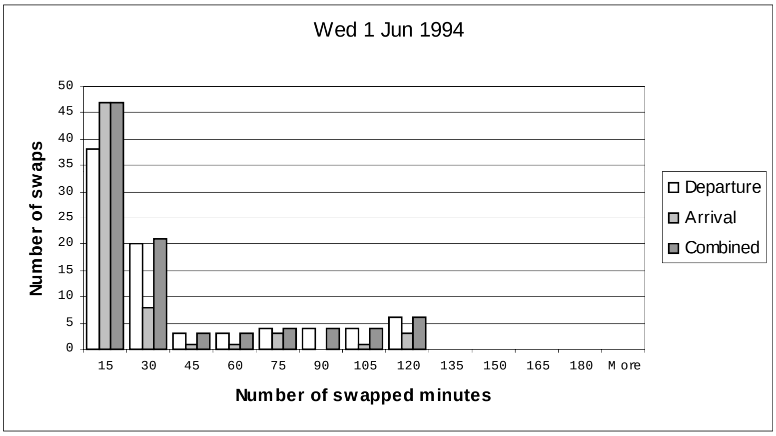

Figure 5. Swapped minutes per flight for test case 2.

For the swap by load contribution algorithm it is not necessary that the two flights are shifted over the same length. The minutes that both flights are swapped for test case 1 are summarised in Figure 6. In this graph f_1 is swapped forward and f_2 is swapped backward in time, respectively. The figures indicate that the flight that is swapped backward in time incurs a longer delay, than the timegain of the flight that is swapped forward in time. Swapping on load contribution may thus lead to more possibilities for swapping, but these extra swap possibilities may come at the cost of a higher total delay. This is not surprising, since it is not possible to decrease the total delay by swapping flights, if the slot allocation scheme is practically optimal with respect to total delay (for details see [7]). Note, however that not all the swaps at load contribution introduce extra delay.

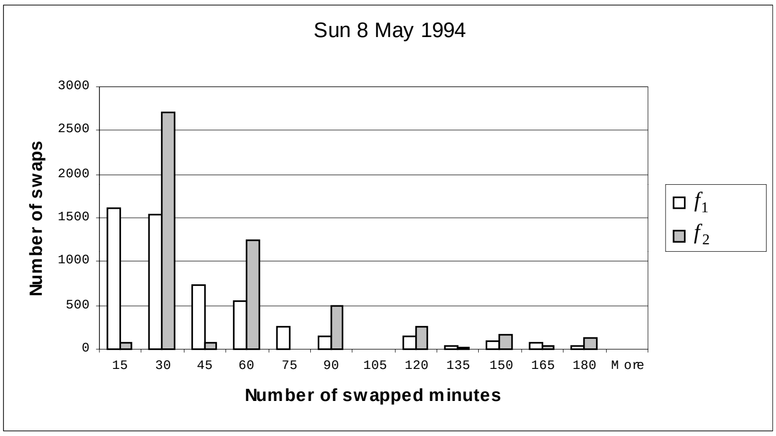

Figure 6. Swapped minutes for both flights in load contribution algorithm for test case 1.

Test case 2 for swapping at load contribution is presented in Figure 7. It exhibits the same type of results as for test case 1. The difference in delay and timegain is more pronounced than in test case 1. This is again due to the particular demand structure of both cases.

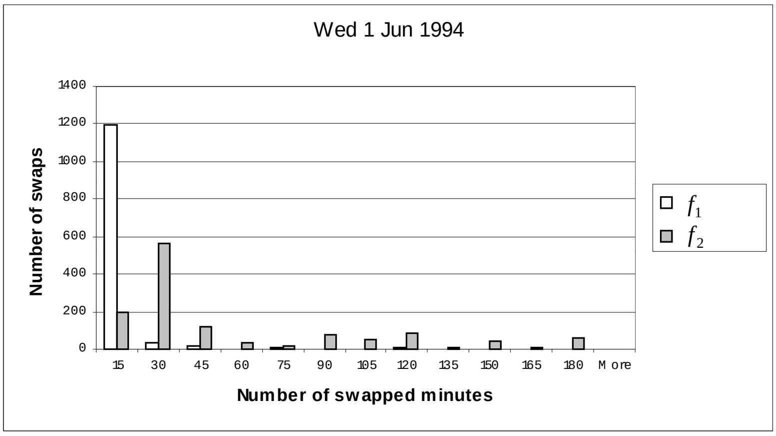

Figure 7. Swapped minutes for both flights in load contribution algorithm for test case 2.

Summarising the numerical results we may conclude that the possibilities for slot swapping look very promising. The three algorithms suggest that a slot allocation scheme may allow swaps for a significant percentage of delayed flight, and moreover, the extra delay that a swap may introduce looks moderate. Of course, swapping in an optimal allocation scheme introduces extra delays. Whether these extra delays are acceptable requires an analysis of costs and benefits.

4 Operational Issues

4.1 Application

A number of operational issues are discussed in [5]. There are two main actors in the process of slot swapping, viz. the Airline Operators and the CFMU. In this process the Airline Operations Center (AOC) decides which flights should be swapped and they send a request to the CFMU. The reasons for choosing particular flights for swapping can be, for instance, commercial sensitivity of a certain flight, number of passengers for connecting flights, or the influence of delays on the rest of the Airline schedule. Obviously a request for swapping cannot be done before a slot has been allocated. When a slot swap has been executed the flight plan of the particular flight must be updated. This influences all the ATC planning processes that this flight is involved in. In particular there is an immediate influence on the departure planning for this flight. Depending on the status of the planning a slot swap may lead to a change in the departure database or it may even necessitate a change in the departure plan. This implies that a possible slot swap must be performed well before the departure planning for the involved flights has been finalised.

One can think of two ways for performing the slot swapping process depending on which actor has the possibility to check the feasibility of swaps. In the first case the AOC has insight into the load of the regulated sectors and in the flight plans of the involved flights, including the ETAs at the sectors. The AOC can then check the feasibility of a swap, with the algorithms presented in this paper, before they submit a swap request to the CFMU. The AOC can even search for swap candidates. In the second case the AOC has only limited insight into flight data and the slot allocation scheme. In this case the AOC can only send swap requests to the CFMU and all the feasibility checks have to be performed by the CFMU. In both cases of course the swap request has to be approved by the CFMU.

The algorithms in this paper check the feasibility of one swap at the time. After a swap has been approved, the slot allocation scheme has to be updated to represent the new situation. This is a minor update of the scheme. The feasibility of a next swap has to be checked using the new slot allocation scheme. In the case where AOCs check the feasibility of swaps, it is important that they check the feasibility for the up-to-date situation. This matter requires attention when considering an implementation for this case.

4.2 Benefits

The most important benefit of slot swapping is an increased flexibility for the Airline Operators. Airlines can give priority to a flight with many passengers to decrease the total passenger delay. Another consideration may be to give priority to a flight with many connecting passengers. In this way they can reduce delays for connecting flights, or to decrease the number of passengers missing their connecting flights. In general an Airline Operator will give priority to a flight for which the delay has the most influence on other operations. The immediate benefit is not a decrease of the delays for the swapped flights themselves (in fact, the total delay for the swapped flights can increase), but a decrease of reactionary delays. These are flight delays that are caused by delays of earlier flights. Examples are delays of connecting flights or of return flights.

An additional benefit of slot swapping can be the reduction of the number of unused slots. In this case the objective of the swap is to delay a flight that is likely to miss its allocated slot. In fact this is an example of slot shifting with two flights (see [5]).

5 Conclusion

In this paper we have presented three applications and algorithms for slot swapping: swap at departure time, swap at sector arrival time, and swap at load contribution. These are more general than the swapping applications based on Most Penalising Regulations presented in [5] and include the possibility of swapping flights departing from different airports.

We have implemented the algorithms in a prototype. Our experiments indicated that there exists swap opportunities for a significant percentage of the delayed flights. The application swap on departure time finds a swap for about 35 percent of the delayed flights. The same is true for the swap at sector arrival. The application swap at load contribution, which is much more flexible, even finds a swap for about 90 percent of the delayed flights. We must say that, since this information was not included in our test data, we did not take into account different airlines, so in our experiments any pair of flights for which a swap is feasible can indeed be swapped.

The most important benefit of slot swapping is that it gives airlines the possibility to decide on priorities among their own flights. A swap in itself does usually not decrease the total delay of the involved flights, but it may decrease the passenger delay as well as reactionary delays. Since a swap is only allowed if it does not cause capacity overload, swapping is not expected to complicate Air Traffic Control. The costs of enabling slot swapping are mainly the costs of giving airlines access to the CFMU data. This data is already available for some airlines.

In the first phase of slot swapping only flights of the same airline (or alliance of airlines) are swapped. However, our results show that swapping flights of different airlines can also be interesting. Clearly, this requires a method to guarantee that swapping is on the longer term beneficial for all the involved airlines.

Although our results are based on a prototype and the operational consequences of the applications have to be investigated further, we conclude that the presented slot swapping applications and algorithms are very promising and that there are good prospects for using them in practice.

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